COE CST Fifth Annual Technical Meeting

TASK 241. High Temperature, Optical Sapphire Pressure Sensors for Hypersonic Vehicles

PI: William Oates
PhD Students: Justin Collins, Harman Singh Bal, Peter Woerner

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Arlington, VA

Center of Excellence for Commercial Space Transportation

Overview

- Team Members
  - William Oates, Justin Collins, Harman Singh Bal, Peter Woerner (FSU)
  - Collaborators: Mark Sheplak & David Mills (UF)
- Motivation
- High temperature experiments
- Theory and modeling of laser machined sapphire
- Conclusions and future work
- Schedule

Team Members

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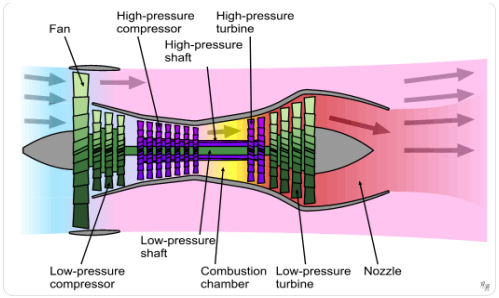
- PI: William Oates, PhD student: Justin Collins (FSU)
- Collaborators: Prof. Mark Sheplak & Post doc: Dr. David Mills (UF)
- Acknowledgements
  - FAA COE-CST
  - Space Florida Matching Funds

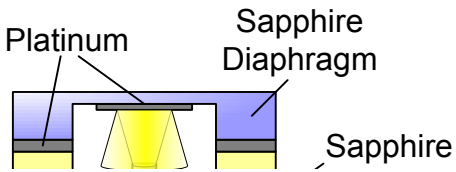
Motivation and Overview

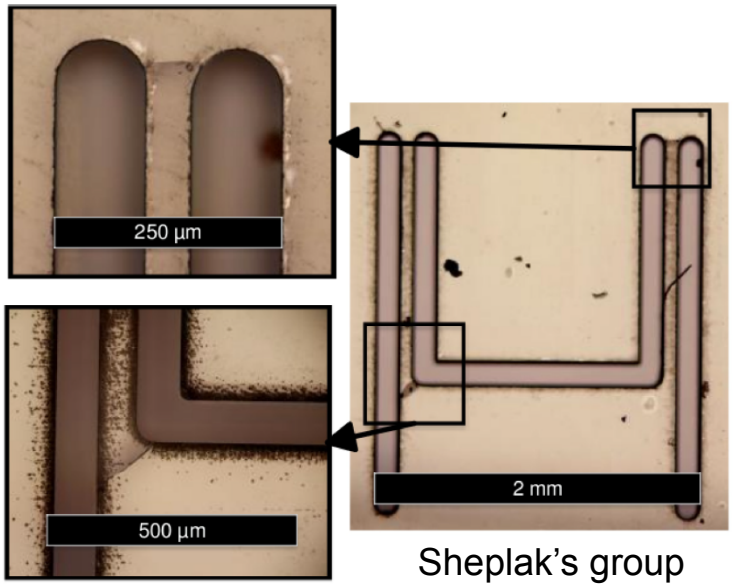
- Lack of sensor technology in >1000°C environments
  - Hypersonic vehicles
  - Gas turbines



- Pressure sensor technologies
  - Capacitive, piezoresistive, optical
  - Optical: no EMI, high temperature capability, simple fabrication; packaging/ manufacturing challenges

- Sapphire optical sensing
  - Laser ablation and spark plasma sintering
  - Impact on structural integrity?

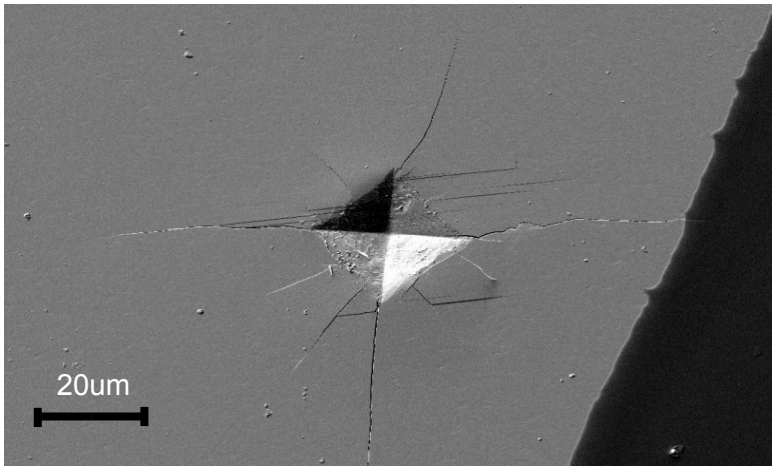


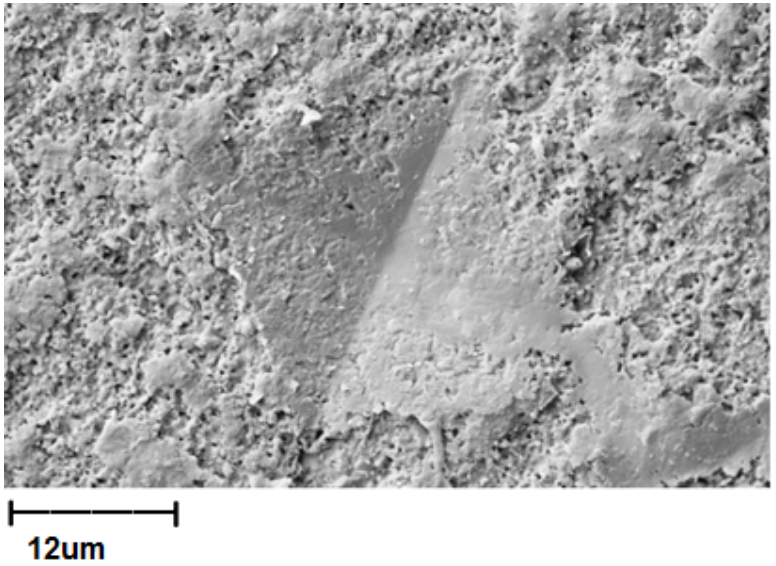


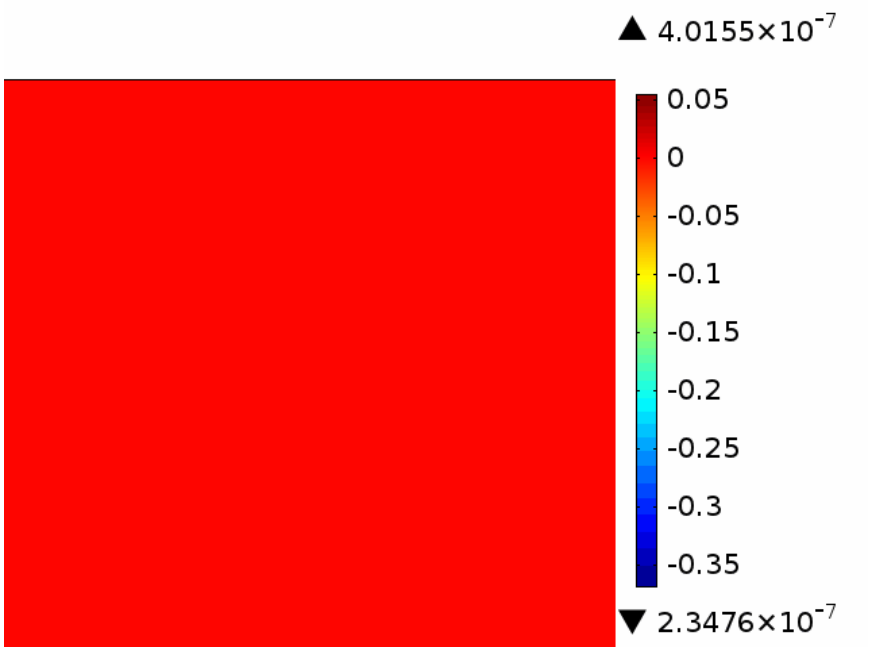
Sheplak's group

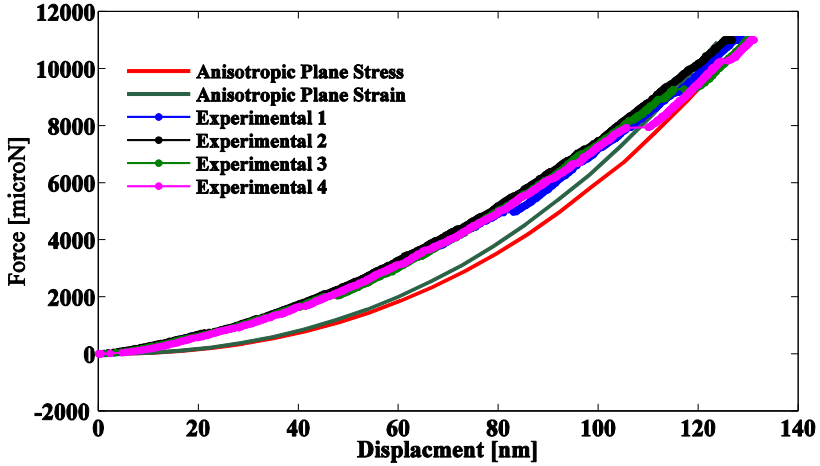
http://www.nasa.gov/centers/ames/research/2007/faq-shuttlereentry.html
http://en.wikipedia.org/wiki/File:Turbofan_operation.png

Nanomechanics of Sapphire



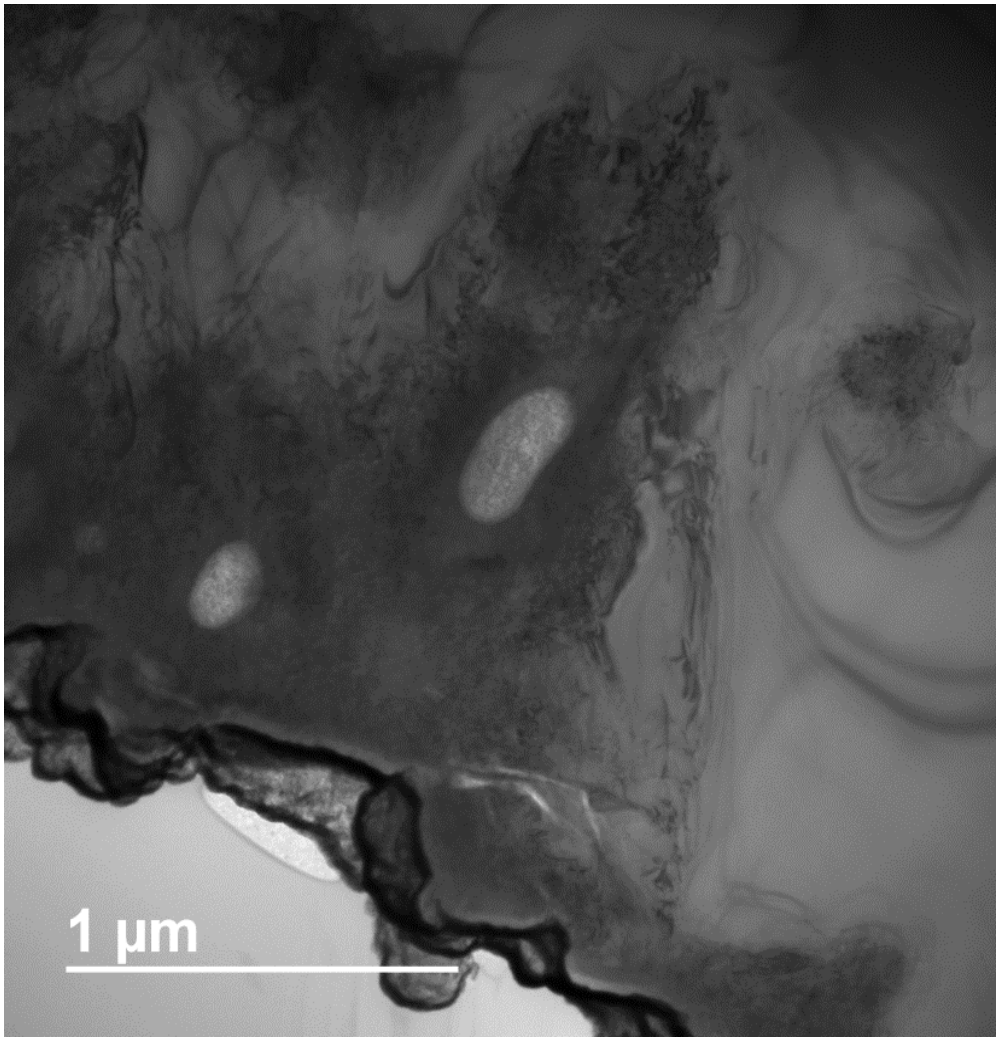






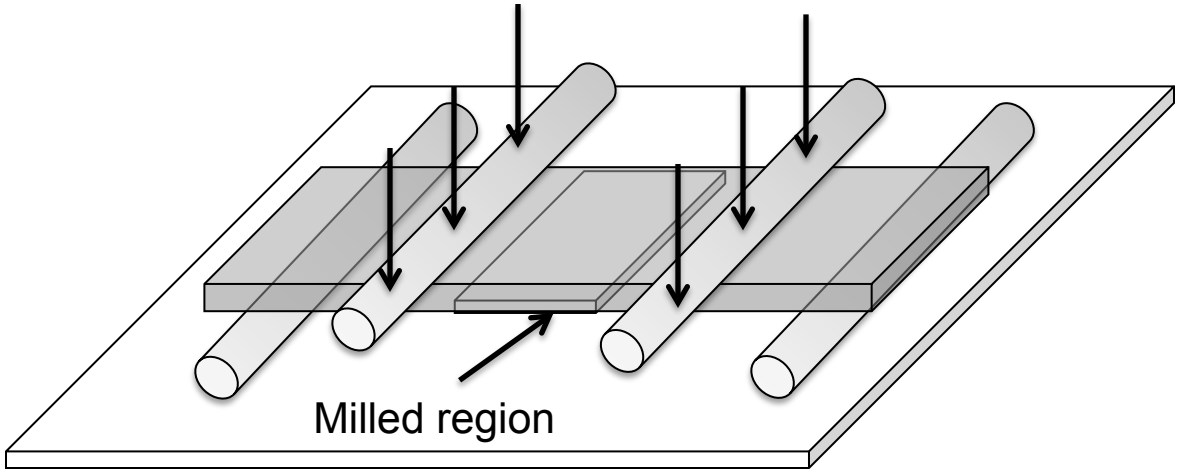
Nanoscale Laser Damage

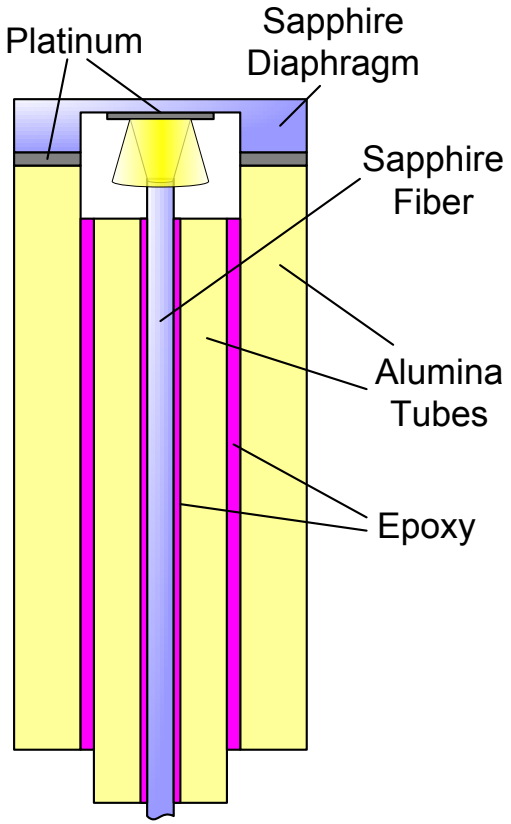
- Laser machining (UF—Sheplak's group)
  - 10 picosecond pulsed laser
  - Varying fluence and frequency rates
- Transmission electron microscopy (TEM)
  - National High Magnetic Field Laboratory
  - Presence of laser induced dislocations

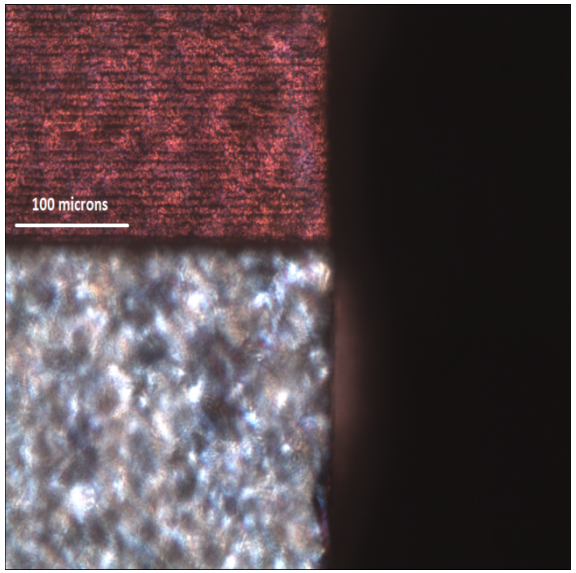


Strength Characterization

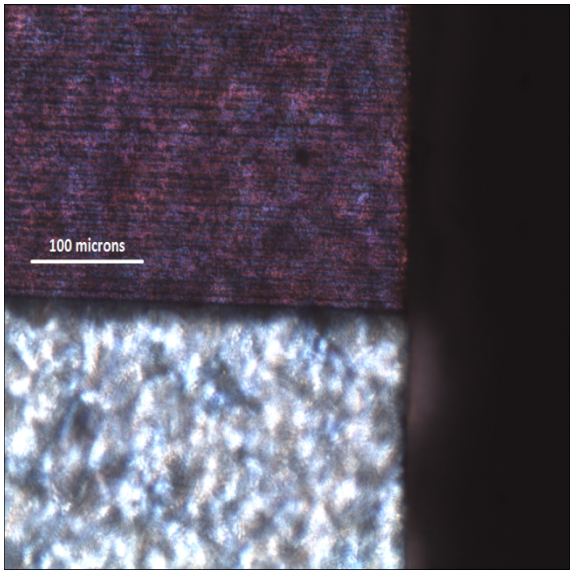
- Sensor reliability
  - Target: measure pressure up to 1000 psi @ 750-1600°C
- Thermomechanical flexural testing
  - 4-point bending
  - Laser machined sapphire (16×6×0.1mm^3)
    - Milled center region—20 μm depth



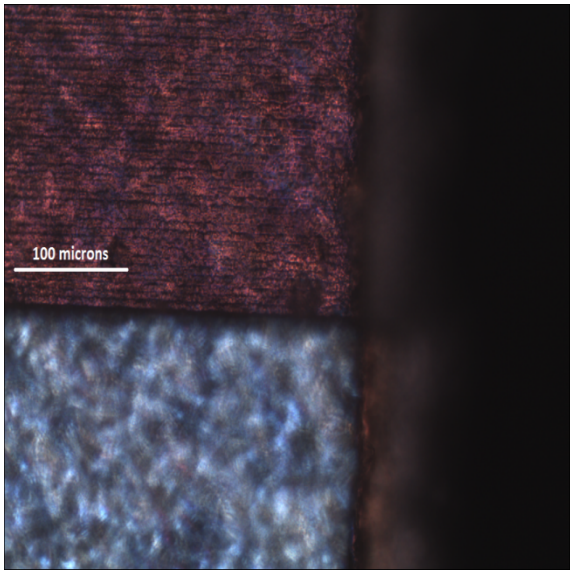




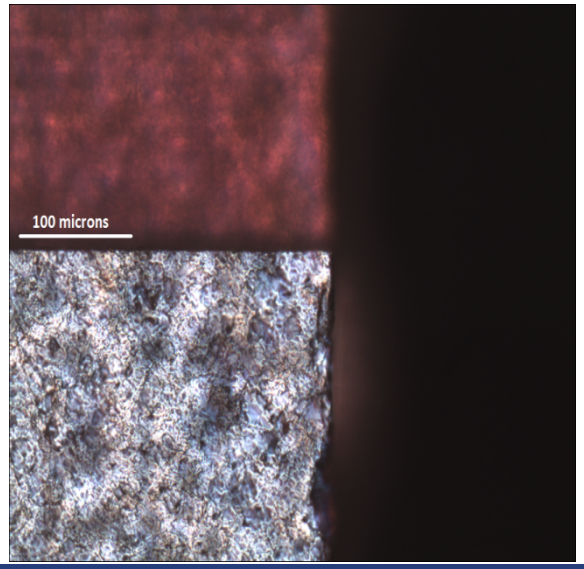
Room Temperature

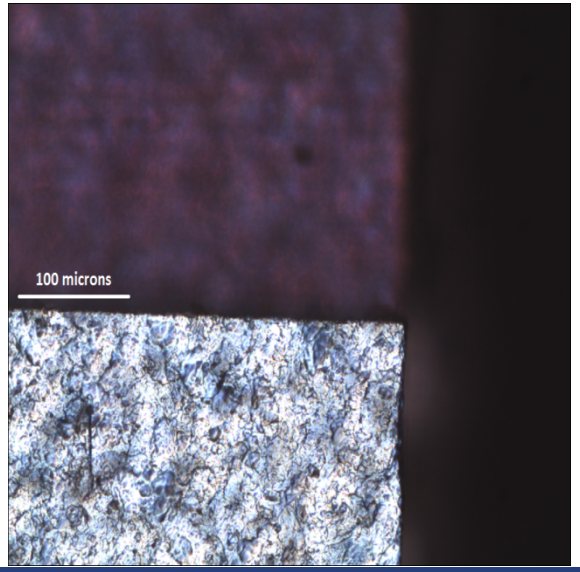


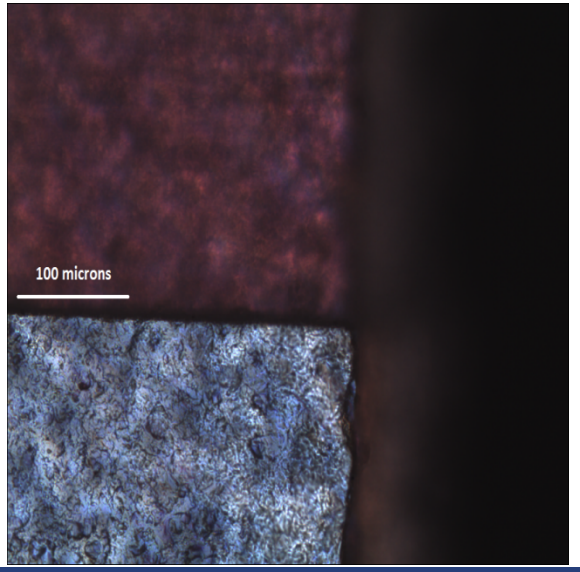
Tested at 950°C



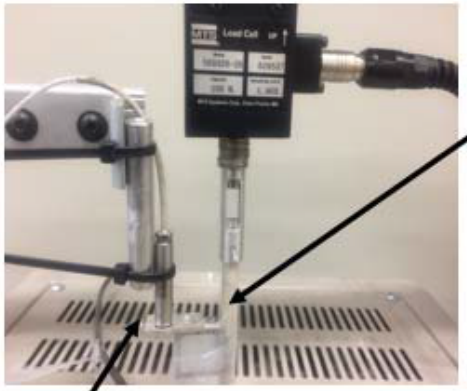
Tested at 1300°C





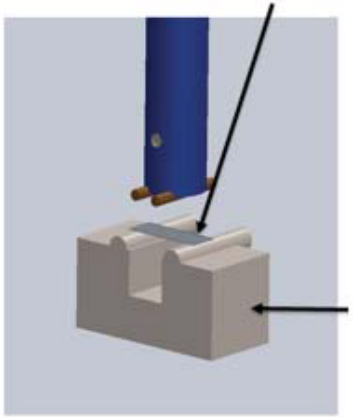


Experimental Set-up



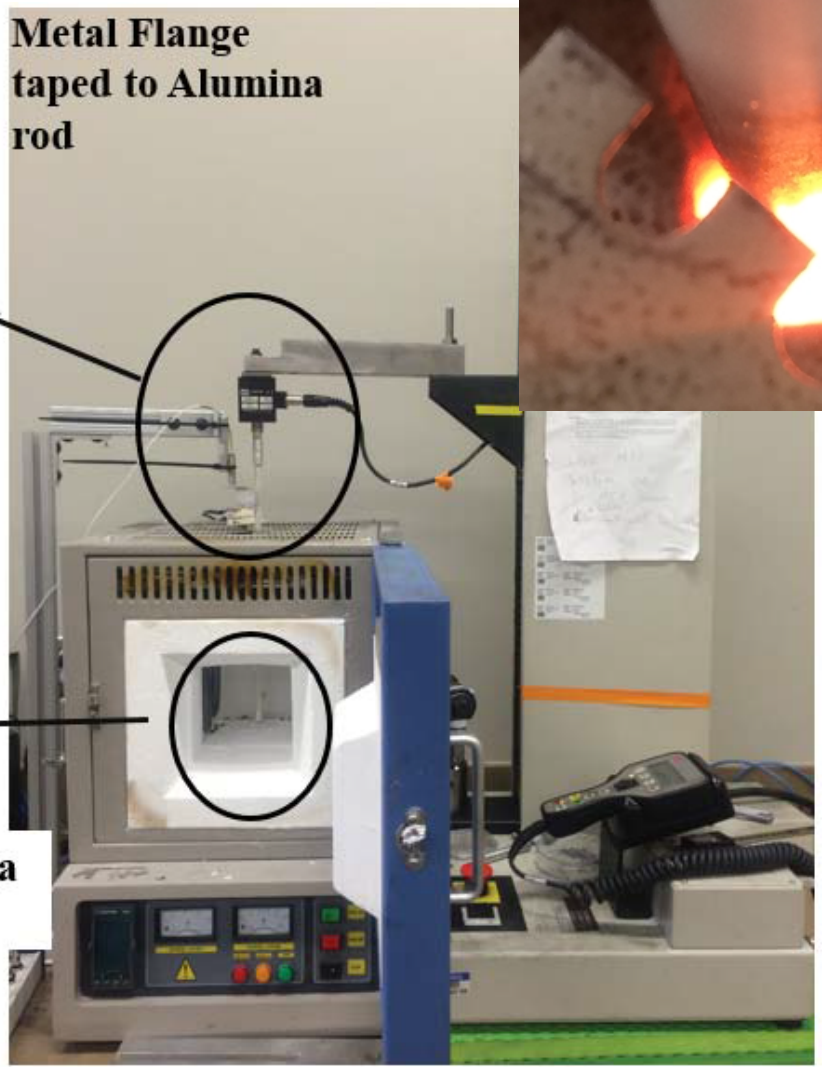
Capacitor Probe

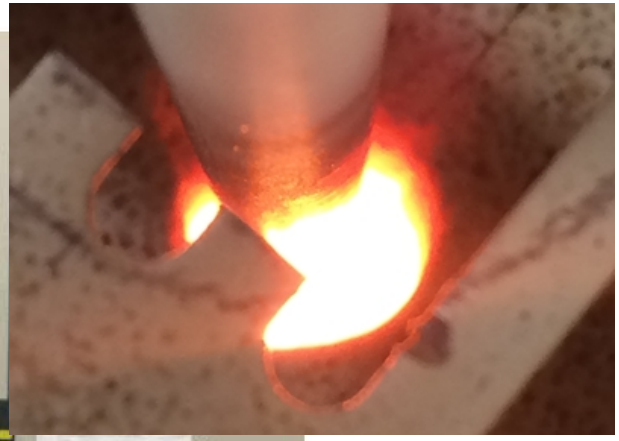
Sapphire Specimen



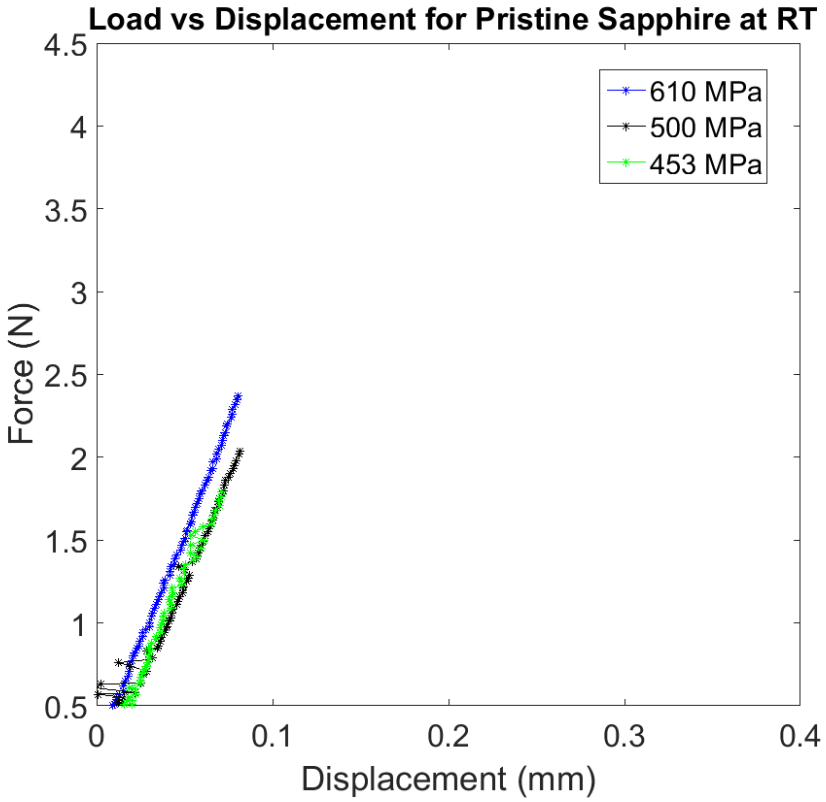
Alumina Block

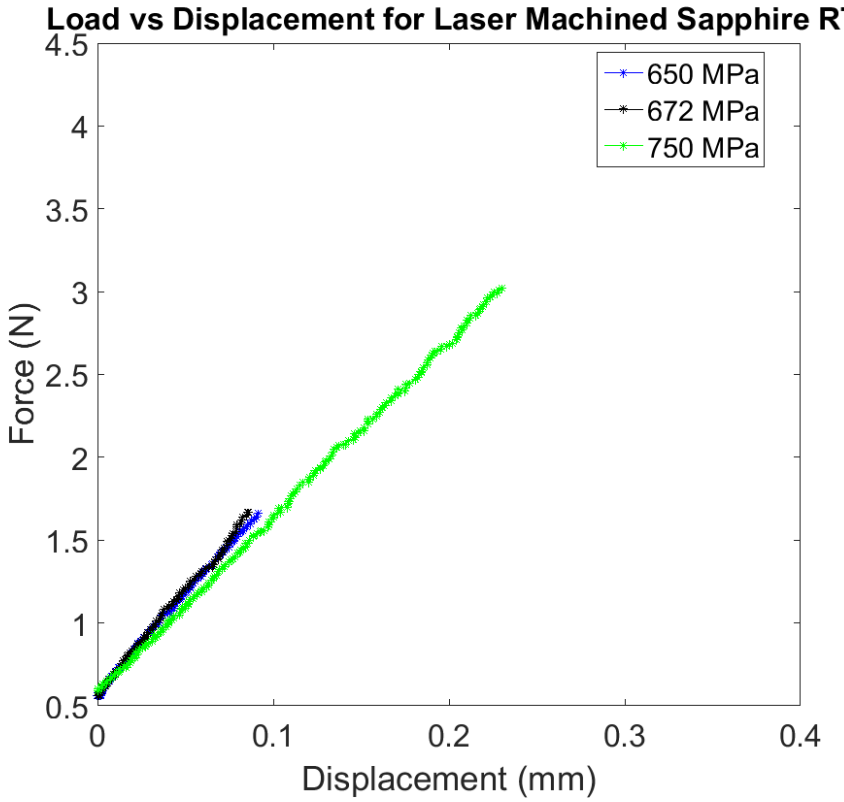
Metal Flange taped to Alumina rod

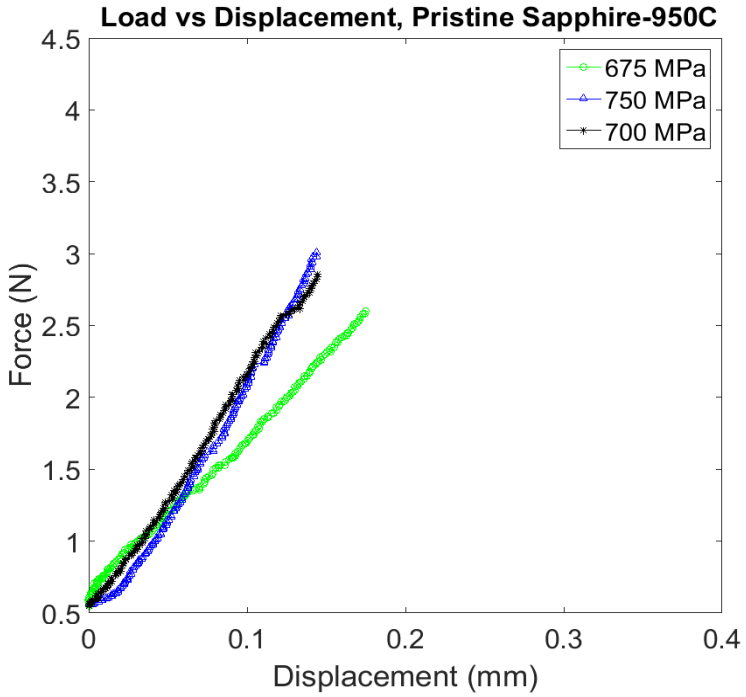


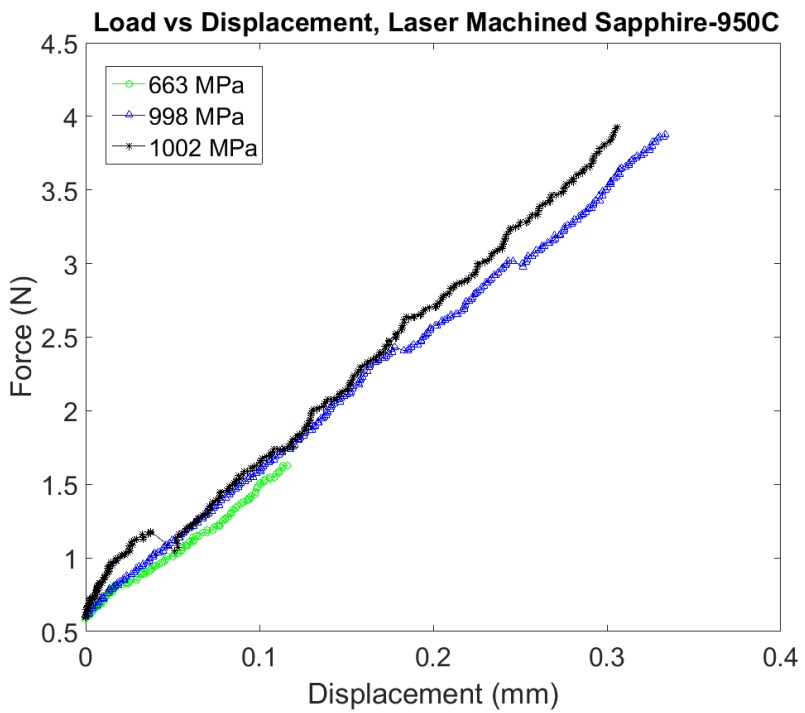


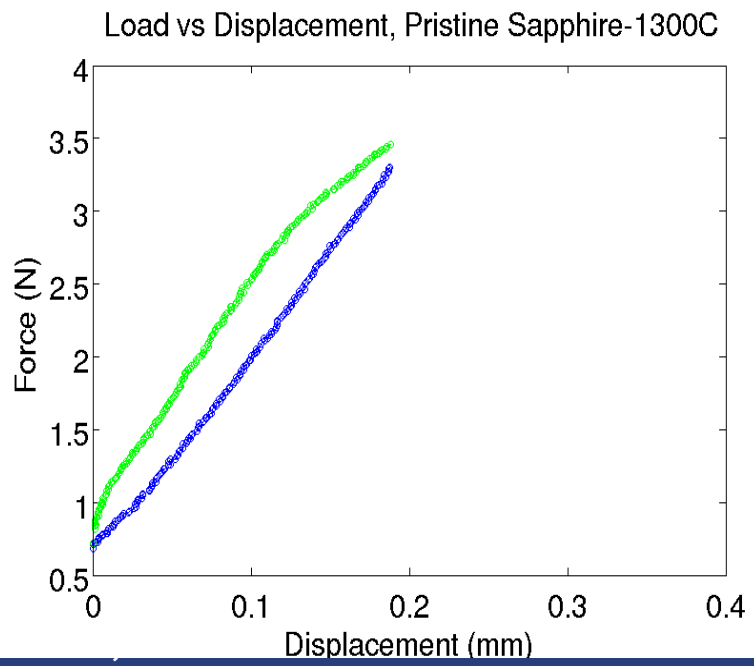
Experimental Results

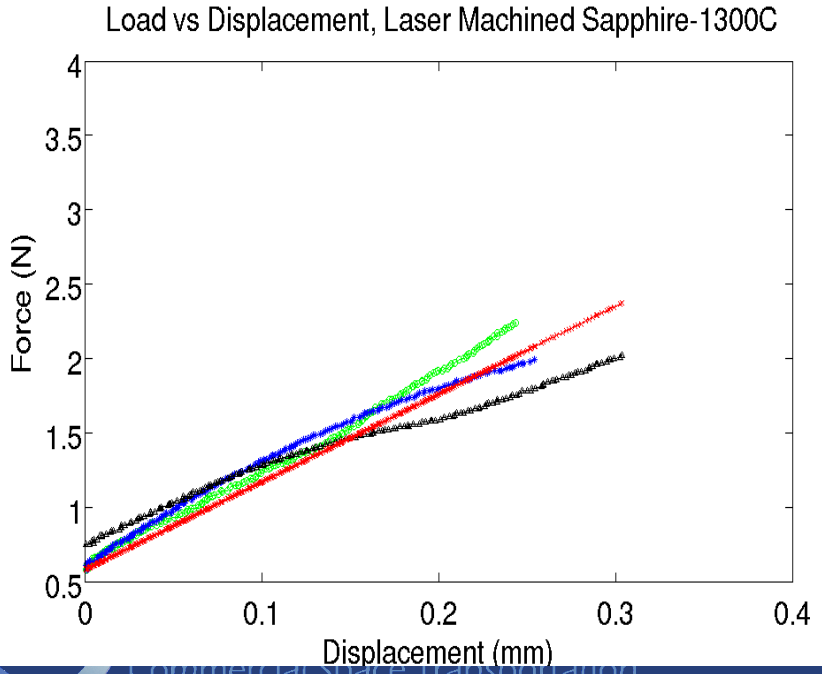




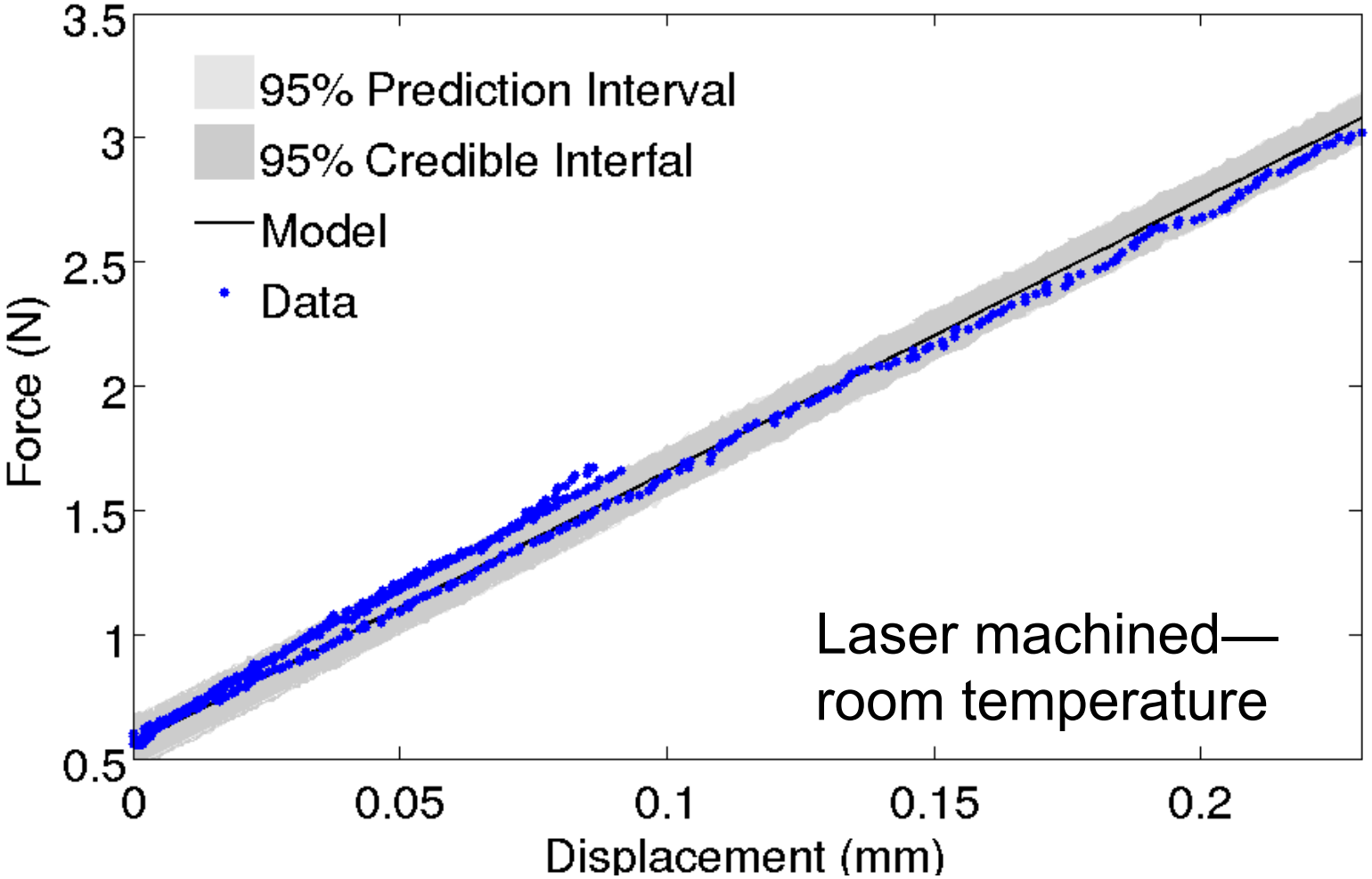

Load vs Displacement, Pristine Sapphire-950C
675 MPa
750 MPa
700 MPa
Force (N)
Displacement (mm)


Load vs Displacement, Laser Machined Sapphire-950C
663 MPa
998 MPa
1002 MPa
Force (N)
Displacement (mm)


Load vs Displacement, Pristine Sapphire-1300C
Force (N)
Displacement (mm)

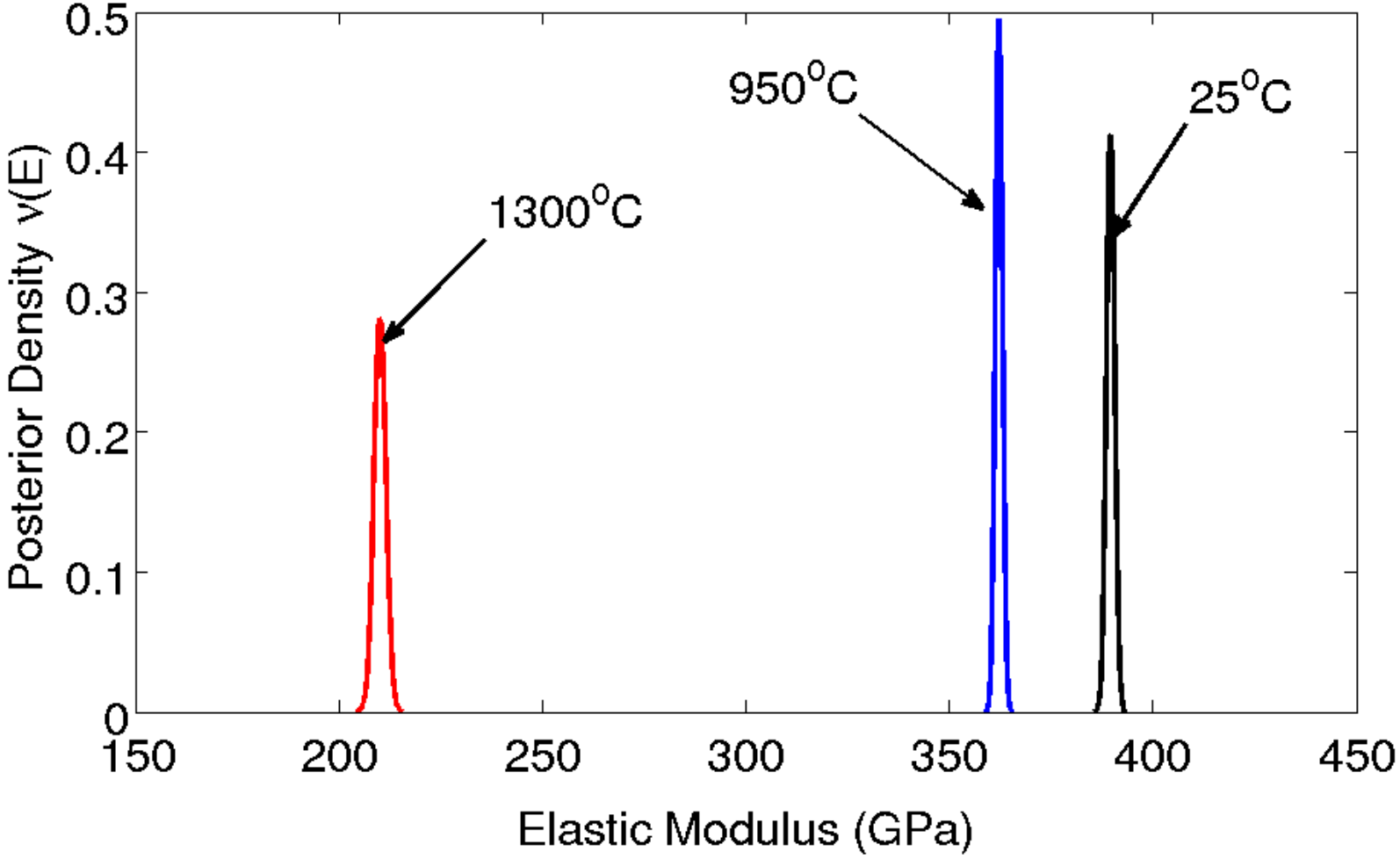

Load vs Displacement, Laser Machined Sapphire-1300C
Force (N)
Displacement (mm)

Bayesian Uncertainty Analysis



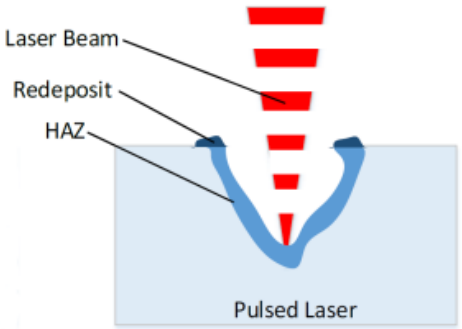
Uncertainty of Elastic Modulus

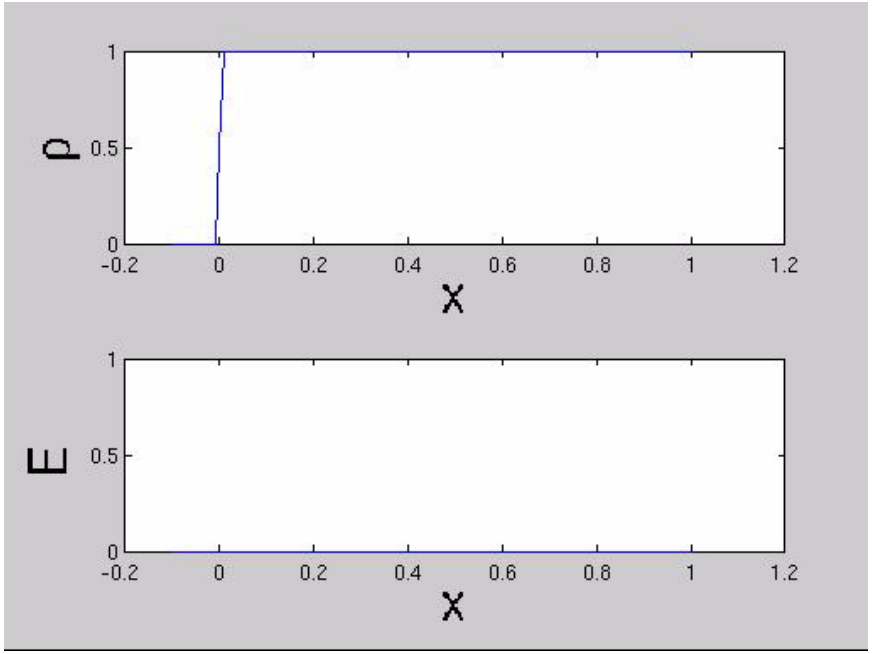
Laser machined specimens

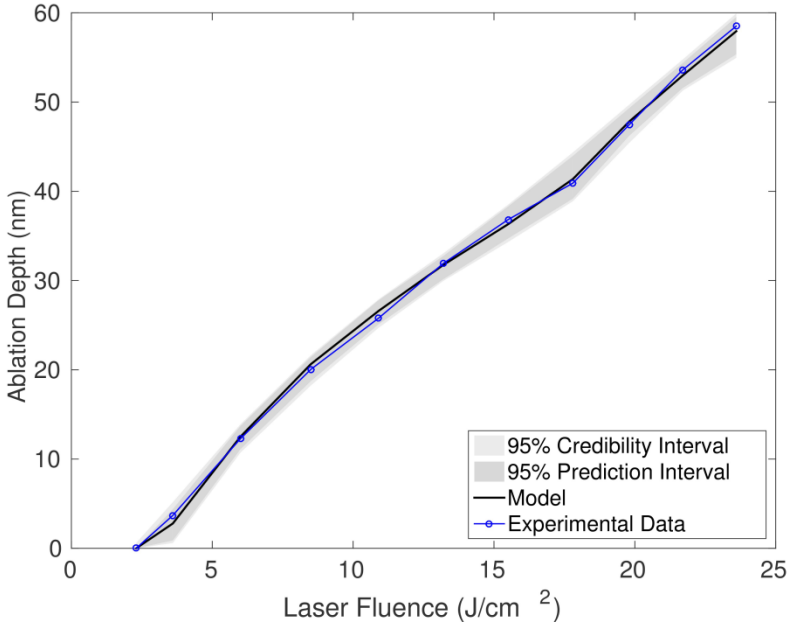


Overview of Laser Ablation

- Multiphysics model developed
- Validated using Bayesian statistics in light of data from the University of Florida
- Model couples electromagnetics of light with electronic structure evolution







Conclusions and Future Work

- Mechanical properties of laser machined sapphire quantified
  - Theory and experimental fracture analysis (prior research)
  - Laser and nanomechanical dislocation measurement and modeling (prior research)
  - Experimental high temperature strength characterization (current efforts)
  - Light-matter interactions and thermomechanical reliability predictions (current efforts)
- Next Steps
  - Dissemination of results
  - Rigorously understand laser machined surface properties
  - System integration and hot jet testing

TASK 241. High Temperature, Optical Sapphire Pressure Sensors for Hypersonic Vehicles

PROJECT AT-A-GLANCE

- UNIVERSITY: Florida State University
- PRINCIPAL INVESTIGATOR: William S. Oates
- STUDENT: Justin Collins

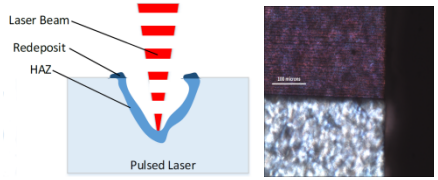
RELEVANCE TO COMMERCIAL SPACE INDUSTRY

- Development of high temperature sapphire based pressure transducers for structural health monitoring.

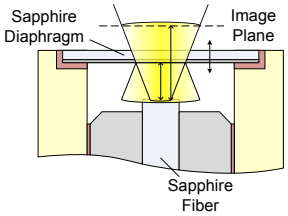
STATEMENT OF WORK

- Implement sapphire based pressure transducer that can operate in high temperature environments (~1000°C to 1200°C)
- Sapphire cannot be manufactured using conventional silicon based chemical etching
- Sapphire based transducer requires a strong understanding of mechanical property changes due to laser micromachining
  - Combined studies of single crystal dislocation mechanics and experimental testing focused on improved sensor reliability and manufacturing methods

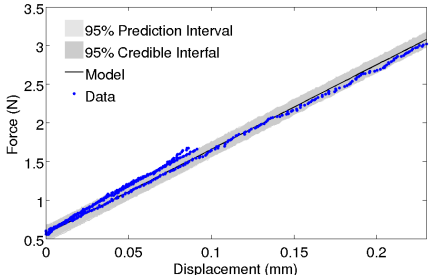
Laser Machining



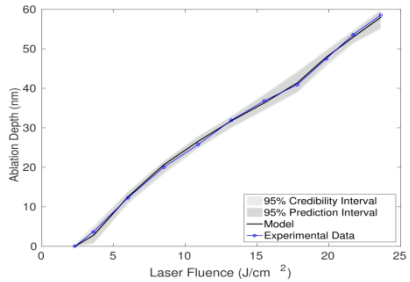
Sensor Characterization



High Temp. Strength Measurement



Laser Ablation Material Physics



STATUS

- High temperature thermo-mechanical set-up designed and validated
- Modulus and strength of sapphire and alumina characterized from room temperature to 1300°C
- Material physics of laser ablation analyzed over broad range of laser fluence conductions
- Uncertainty in modulus and laser ablation quantified using advanced Bayesian statistics algorithms

FUTURE WORK

- Rigorous assessment of damage evolution during loading and unloading of laser machined sapphire specimens
- Pressure transducer characterization with Univ. of Florida